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938nm Nd-doped High Power Cladding Pumped Fiber Amplifier

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938nm Nd-doped high power cladding pumped fiber amplifier

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Abstract: 2.1W of 938nm light has been produced in an Nd^{3+} doped fiber amplifier. Wavelength dependent bend losses can be employed to minimize 1088nm amplified spontaneous emission giving the optical fiber a distinct advantage over bulk media.

OCIS Codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (140.3530) Lasers, neodymium

It has long been a challenge to achieve high power laser or amplifier operation of the $^4F_{3/2}$-$^4I_{9/2}$ transition of neodymium based laser media because of the 3-level nature of the transition and competition from the $^4F_{3/2}$-$^4I_{11/2}$ 4-level transition. Multi-watt operation on this transition has recently been achieved in crystal hosts such as YAG and YVO_4 [1]. However, laser or amplifier operation of the $^4F_{3/2}$-$^4I_{9/2}$ transition in glass hosts or optical fiber hosts to date has been limited to power ranges on the order of 100mW [2]. Silica glass hosts offer many advantages over their crystal counterparts, such as broader tuning ranges (900nm to 950nm) and for specific material compositions, more favorable branching ratios for the $^4F_{3/2}$-$^4I_{9/2}$ transition [2]. Optical fiber hosts also offer the potential of using wavelength dependent bend induced losses [3] to create a distributed filter to suppress laser action on the $^4F_{3/2}$-$^4I_{11/2}$ transition. We are developing this amplifier as a 938nm source for sum-frequency mixing with a 1583nm high power erbium fiber laser in order to achieve high power 589nm light for guide star applications for astronomy [4].

There are a number of challenges to be overcome in order to get high power operation of the $^4F_{3/2}$-$^4I_{9/2}$ transition in an optical fiber. Because the desired 3-level transition is competing with an undesired 4-level transition, pumping to transparency guarantees large gain in an undesired wavelength band. Further, cladding pumping, the standard method for achieving high output power from a fiber laser or amplifier is not intrinsically compatible with 3-level laser systems as the pump and signal beam do not have high overlap and thus it is difficult to achieve high inversion in the laser media. However, the materials with the best branching ratios into the $^4F_{3/2}$-$^4I_{9/2}$ transition (nearly pure fused silica) are also the ones into which neodymium is the least soluble. This increases the attractiveness for an optical fiber host due to the potential of long interaction lengths, which are preferred for low doping concentrations.

Of particular concern is the neodymium concentration level at which significant quenching occurs. We obtained several samples of standard neodymium-doped optical fiber with varying concentrations for characterization for use in our amplifier. The samples were co-doped only with germanium to maximize the branching ratio into the desired transition [2]. We were also able to obtain samples of the preforms from which these fibers were drawn. Using the preform samples we measured the upper state lifetime of the laser transition. In all samples, we found there was a 0.4-0.8μs component (due to quenched sites) and a 470μs component (due to active sites). By comparing the relative strengths of these components we were able to estimate the percentage of ions that were quenched. A second measurement of small signal absorption at 905nm and small signal gain at 905nm with nearly complete inversion (achieved by pumping a short length of fiber in the core with 650mW of 830nm pump light from a Ti:Sapphire laser) was made on the optical fibers. This measurement followed the techniques used by Giles to characterize rare earth doped optical fibers for modeling [5] and permitted an independent estimate of the number of quenched sites. The second measurement also permitted us to understand the gain and absorption spectrum of our fiber samples. The results of these measurements are plotted in figure 1 below.

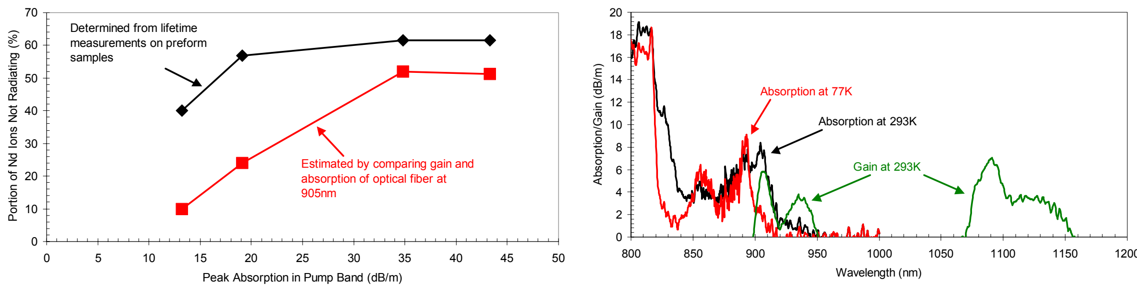

Fig. 1 LHS: percent of non-radiating neodymium ions as a function of absorption in the pump band (black line, estimated from preform lifetime, red line, estimated from fiber gain/absorption measurement). RHS: gain (green line) and absorption spectra (black line 293K, red line 77K) of one of the neodymium doped optical fibers.

In figure 1 on the left hand side (LHS), one observes the optical fiber and the preform from which it came have the same general trend with respect to quenching vs. concentration. However, it appears, the optical fiber shows significantly better performance than would be expected from the preform measurement alone.

In figure 1 on the right hand side (RHS), a typical absorption and gain spectra for the fibers is plotted. Data below 800nm has been suppressed. Because the fiber core is not single mode below 800nm, there were unacceptably high errors in the data in that region. We have also measured the fiber absorption at 77K. The absorption in the 920nm-950nm region, of particular interest to our application, is virtually eliminated at 77K. Thus, the transition is effectively a 4-level transition when the fiber is cooled, making it much more compatible with cladding pumping. Liquid nitrogen cooling of a bulk laser gain media, would be difficult to achieve in a practical laser application. However, the fiber amplifier is much better suited to immersion in liquid nitrogen it can be coiled and bent easily. This provides for a simple and robust means to isolate the remaining amplifier components such as the coupling optics for the signal and pump beams from the 77K temperatures. A fluorinated glass pump cladding ensures the guiding properties of the optical fiber operate essentially the same at 77K as at 293K.

The issue of competition from the 1088nm transition remains, however. Most optical fiber amplifiers are coiled, by choosing the appropriate bend radius for the coiling we can create high loss at 1088nm with minimal losses at the 938nm signal wavelength. To understand this better, we measured the bend losses of the fiber at 938nm and 980nm and compared them to losses expected from theory [3]. We also used the theoretical expressions to what the losses would be at 1088nm. These results are shown in figure 2 below.

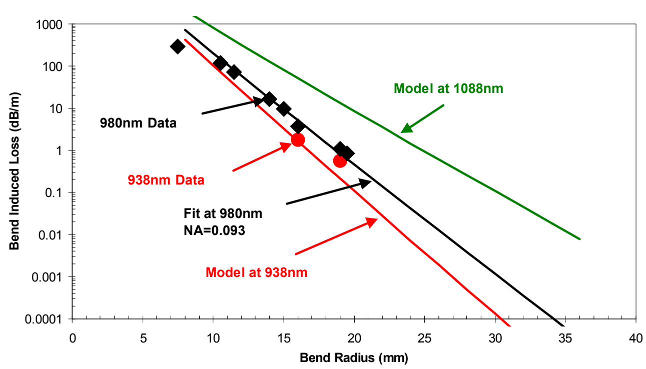

Fig. 2: Measured bend loss (dB/m) as a function of bend radius (mm) for 980nm (black dots) and 938nm (red dots). A bend loss model has been fit to the data (938nm red line, 980nm black line and 1088nm green line). The fiber numerical aperture was used as a fit parameter and a value of 0.0932 was found to provide the best fit. An independent measurement of the numerical aperture from the manufacturer found a value of 0.09.

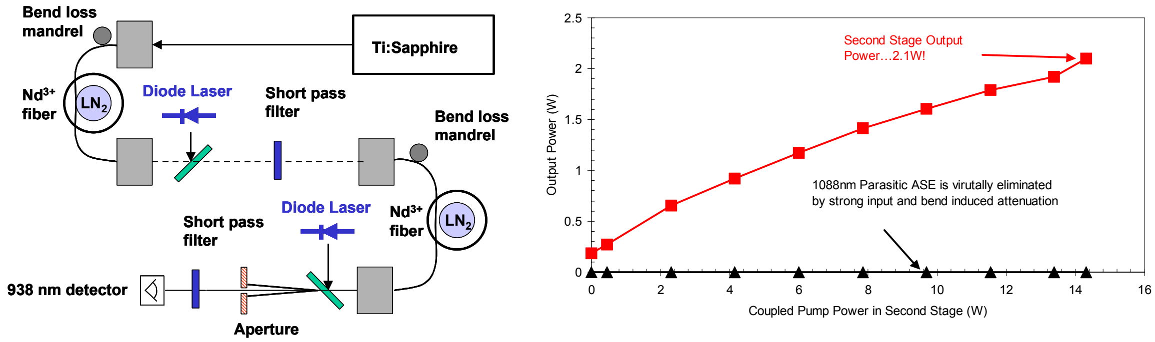

Fig. 3: LHS: schematic of amplifier configuration for 2.1W output power demonstration. RHS: plot of stage 2 amplifier output showing 2.1W of power at 938nm and excellent suppression of 1088nm ASE power.

In figure 3 above, a two-stage amplifier configuration was employed to maximize the output power of the amplifier. The same type of fiber was used in each stage. The fiber was 100m long in the first stage and 200m long in the second stage. The core of the fiber employed had loss and gain characteristics as measured and reported in figure 1 (RHS) and bend loss characteristics as reported in figure 2. The active fiber had a fluorinated outer region providing a 0.22NA, 200µm diameter pump cladding. The core had a neodymium doped germano-silicate material composition and was 7.5µm in diameter with an NA of 0.09. Peak small signal pump wavelength absorption of 19dB/m at 810nm was measured for light propagating in the core of the fiber. A short pass filter was employed between stages of the amplifier to eliminate amplification of 1088 ASE from the first stage in the second stage. The 938nm signal power and 1088nm parasitic powers were determined by measuring the output power of the fiber at the power meter with and without the short pass filter and employing knowledge of the loss of the filter at 938nm and 1088nm.

2.1W of output power at 938nm has been obtained, which to our knowledge is over an order of magnitude higher than any previously reported results for an optical fiber amplifier operating on the $^4F_{3/2}$-$^4I_{9/2}$ transition of neodymium. Much can be done to improve this result in future design iterations. In particular, understanding of the quenching of neodymium sites was not complete until after the cladding pumped fiber had been obtained. A fiber with small signal absorption of 10dB/m at 810nm would suffer much less from pump losses due to quenching according to the data presented in figure 1. Furthermore, the amplifier fiber in question was much longer than desired resulting in high passive losses due to high scattering out of the fiber core, which is typical in rare earth doped optical fibers. We are presently redesigning our amplifier fiber to minimize quenching and passive losses, which should improve both the amplifier output power and efficiency.

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